Renewable and Sustainable Energy Reviews 16 (2012) 5603–5616

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on effect of phase change material encapsulation on the thermal performance of a system

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ARTICLE INFO

Article history:
Received 11 September 2011
Received in revised form
21 May 2012
Accepted 22 May 2012
Available online 4 August 2012

Keywords:
Phase change material
Encapsulation
Thermal energy storage
Microencapsulated phase change slurry

ABSTRACT

This paper presents a detailed review of effect of phase change material (PCM) encapsulation on the performance of a thermal energy storage system (TESS). The key encapsulation parameters, namely, encapsulation size, shell thickness, shell material and encapsulation geometry have been investigated thoroughly. It was observed that the core-to-coating ratio plays an important role in deciding the thermal and structural stability of the encapsulated PCM. An increased core-to-coating ratio results in a weak encapsulation, whereas, the amount of PCM and hence the heat storage capacity decreases with a decreased core-to-coating ratio. Thermal conductivity of shell material found to have a significant influence on the heat exchange between the PCM and heat transfer fluid (HTF). This paper also reviews the solidification and melting characteristics of the PCM and the effect of various encapsulation parameters on the phase change behavior. It was observed that a higher thermal conductivity of shell material, a lower shell size and high temperature of HTF results in rapid melting of the encapsulated PCM. Conduction and natural convection found to be dominant during solidification and melt processes, respectively. A significant enhancement in heat transfer was observed with microencapsulated phase change slurry (MPCS) due to direct surface contact between the encapsulated PCM and the HTF. It was reported that the pressure drop and viscosity increases substantially with increase in volumetric concentration of the microcapsules.

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Abbreviations: HTF, heat transfer fluid; MPCS, microencapsulated phase change slurry; PCM, phase change material; PCS, phase change slurry; TESS, thermal energy storage system

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http://dx.doi.org/10.1016/j.rser.2012.05.037

Nomenclature

English symbols

C	constant
C_p	specific heat, J/kg K
E	encapsulation efficiency
ΔH	latent heat, J/kg
k	thermal conductivity, W/m K
l	PCM thickness, m
m	mass, kg
Nu	Nusselt number
q	heat flow, W
$\dot{q}$	volumetric heat generation, W/m^3
R	cylinder radius, m
Ra	Rayleigh number
Ste	Stefan number
T	temperature, K

Greek Symbols

β	heat generation parameter
θ	heating/cooling rate, K/min
η	encapsulation ratio
δ	PCM liquid thickness, m

Subscripts

app	apparent
m	melting
encap	encapsulated
eq, p	predicted equivalent
f	fusion
p	predicted
s	solidification
0	outside

Superscripts

m, n	constant

1. Introduction

The energy crisis in year 1971 gave an impetus to search for alternative energy sources as well as other energy saving ways that can fulfill the energy demand. Since then the focus on phase change material (PCM) increased. PCMs are the substances that can absorb, store and release large amount of thermal energy. In 1901, Kyle [1] filed a patent on using palmitic acid and stearic acid to maintain the required temperature during the manufacturing of tin sheets. The total heat addition/release to/from the PCM consists of sensible heat and latent heat. During sensible heating the thermal energy is stored up to the initiation of melting process, whereas, the thermal energy stored during the phase change process is known as the latent heat. One of the major advantages of the latent heat storage system is an isothermal release or gain of thermal energy. In contrast, the temperature decreases/increases during sensible cooling/heating. In a typical working temperature range, the latent heat storage capacity is about 5 to 14 times the conventional thermal energy storage materials such as masonry, rock etc. Thus, the prime advantage of PCM is the substantial reduction in space requirement for the same energy storage compared to that of conventional materials. The high energy storage density characteristic of the PCM has made it a hot topic of research over the last few decades. To this date, enormous work has been carried out to explore the use of PCMs in various applications, namely, building air conditioning [2–5], electronics cooling [6–8], waste heat recovery [9,10], textiles [11], preservation of food, milk [12,13], solar energy storage [14–17], fabrics [18] to name a few.

As compared to solid–solid, liquid–gas and solid–gas PCMs, solid–liquid PCMs have been widely used due to their large heat storage capacity and lesser volume change during the phase change process. There are multiple review papers [2,19–22] that highlight various PCMs and their use for thermal energy storage in various applications as listed previously. Most of the above studies deal with the selection criteria for a suitable PCM depending upon their application.

Besides above, there are also numerous studies that report the preparation and characterization of encapsulated PCMs [23–29]. From previous studies it is evident that PCM encapsulation has a significant influence on the performance of a TESS. Based on the above literature survey, it was noticed that the studies on the effect of various encapsulation parameters, namely, size, shape, core-to-coating ratio, shell material and shell thickness of the encapsulated PCM on the flow and heat transfer characteristics of the PCM is missing. In this regard, the objective of the present study is to highlight the effect of encapsulation parameters on the performance of a TESS as well as on the solidification and melting characteristics of the encapsulated PCMs. The present review mainly focuses on but not limited to the building air conditioning and solar water heater applications.

2. Encapsulation of phase change materials

Encapsulation is a process of covering the PCM (that forms the core part of the encapsulated PCM) with a suitable coating or shell material. This process was first invented by Barrett K Green in the 1940s and 1950s [30] according to [31]. A primary purpose of encapsulation is holding the liquid and/or solid phase of the PCM and keeping it isolated from the surrounding. This ensures correct composition of the PCM that would have otherwise changed due to mixing of the PCM with the surrounding fluid. Other advantages of encapsulation involve reduction in reaction of PCM with the surrounding, flexibility in frequent phase change processes, an increase in heat transfer rate and enhancement in thermal and mechanical stability of the PCM. It can also improve the compatibility of hazardous PCMs that cannot be directly used or immersed in certain applications such as blood transport, food storage, building cooling/heating, etc.

A major concern for the encapsulation of salt hydrates is their corrosive nature with metals and complete solubility in water. In contrast, organic PCMs are non-corrosive and show negligible or incomplete solubility in water. The non-corrosive nature and insolubility in water are the highly desirable characteristics for the PCM. After about 1000 thermal cycles, the diffusion tightness as well as the thermal and structural strength of the encapsulated PCM deteriorates substantially and there is a possibility of absorption of water molecules if the PCM is soluble in water. Hence, encapsulation of organic PCMs is preferred over salt hydrates [32,33]. Mehling and

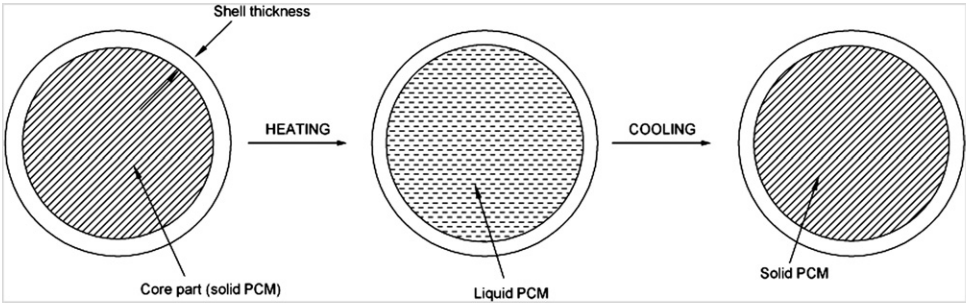


Fig. 1. Structure and working principle of the encapsulated PCM.

Cabeza [33] reported that till date microencapsulation of only organic PCMs has been commercialized. However, most of the organic PCMs are flammable. The flammability can be reduced by encapsulating the PCM with an inorganic material [34]. Hart and Work [35] suggested that certain additives, namely, decabromodiphenyl oxide, octabromophenyl oxide, antimony oxide etc. can be added to the encapsulated PCMs as a flame retardant. Due to encapsulation, these PCMs can be directly mixed or suspended in the surrounding medium.

Diffusion tight bonding between the PCM and the shell material prevents the spillage of the PCM when it is in liquid state. Fig. 1 shows the structure and working principle of the encapsulated PCM. The encapsulated PCM contains PCM as a core part and shell material as the encapsulant. Sometimes, an additional air pocket is provided inside the core part to accommodate the change in volume during phase change process. Cristopia Energy Systems [36] manufacture such type of nodules. The shell should be strong enough to sustain the stresses that are generated due to volumetric changes during the phase change process of the PCM. The hydrophobic PCMs can prevent the solubility of PCM into water. This avoids the contamination of the water that would have otherwise resulted in hazardous effects to the human health. The thickness of the coating material is one of the critical parameters in assessing the effectiveness of the encapsulated PCM. A substantially thin PCM capsule can have inferior structural and thermal strengths, whereas, excessive thickness of the coating material can reduce the amount of PCM inside the shell, thereby increasing the container volume. In subsequent section, a detailed study of effect of the encapsulation thickness on the performance of a TESS is presented.

The working principle of the encapsulated PCM as shown in Fig. 1 can be explained as follows. In solid state, the supplied heat to the PCM increases its temperature until it reaches the melting point. The PCM temperature remains constant throughout the melting process. During this phase change process substantial amount of heat is stored. The molten PCM transforms to solid when exposed to the surrounding with a temperature lower than its melting point. The phase transformation occurs through release of thermal energy during sensible cooling and the phase change process from the liquid to solid state. The phase change of PCM from solid to liquid phase and from liquid to solid phase are termed as charging and discharging processes, respectively.

There are two broad methods, namely, physical and chemical for the manufacture of the microencapsulated PCM. Fig. 2 shows the flowchart of different manufacturing techniques of the microencapsulated PCM. Physical methods result in a relatively large size, rough surface microcapsules as compared to chemical methods. Hawlader et al. [31] reported a substantial drop in heat storage capacity with the physical methods as compared to that of chemical methods. Among the chemical methods, in situ polymerization was found to be a favorite choice for the encapsulation due to its excellent shell structure and smaller capsule size [37].

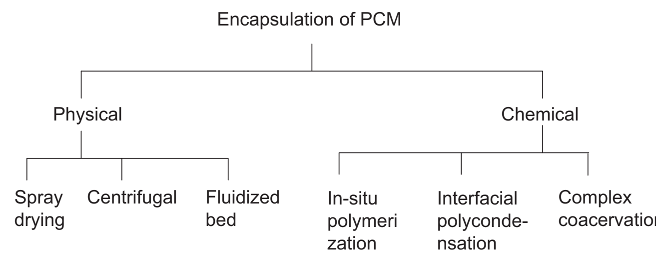


Fig. 2. Flow chart showing different manufacturing techniques of microencapsulated PCM.

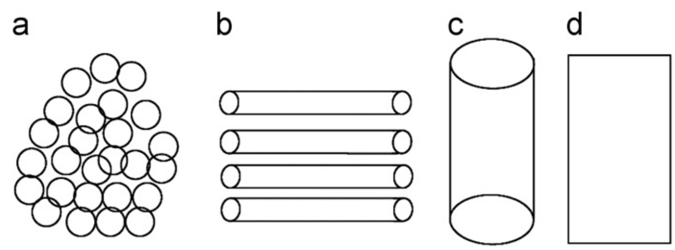


Fig. 3. Different geometries for encapsulation of PCM (a) spherical (b) tubular (c) cylindrical and (d) rectangular.

3. Nomenclature

3.1. Encapsulation ratio

Encapsulation ratio, η indicates the effective performance of a PCM inside the capsule [38]. The encapsulation ratio is defined by the following formula [34,39]:

$$\eta = \frac{(\Delta H)_{m,encapPCM}}{(\Delta H)_{m,PCM}} \times 100 \tag{1}$$

3.2. Encapsulation efficiency

The encapsulation efficiency, E is given by the following formula [40]

$$E = \frac{(\Delta H)_{m,encapPCM} + (\Delta H)_{s,encapPCM}}{(\Delta H)_{m,PCM} + (\Delta H)_{s,PCM}} \times 100 \tag{2}$$

The melting latent heat and the latent heat of crystallization are identical for a perfectly reversible PCM. The difference between the two arises due to different melting and solidification points. The difference in melting and solidification point may be attributed to the effect of subcooling, or incongruent melting.

Higher encapsulation efficiency is desirable due to its higher mechanical strength and leak proof characteristics. The phase

change enthalpy of the encapsulated PCM is a strong function of encapsulation ratio and encapsulation efficiency [38]. Hawlader et al. [31] mentioned that the encapsulation efficiency is a critical parameter in determining the quantity of PCM to be encapsulated.

4. Types of PCM encapsulation based on size

Based on size, encapsulated PCM can be classified as follows

i) macro (above 1 mm),
ii) micro (0–1000 μm) and
iii) nano (0–1000 nm) encapsulated PCM.

Macroencapsulation is a common way of encapsulating the PCM for thermal energy storage applications. The container shape may be spherical, tubular, cylindrical or rectangular as shown in Fig. 3. Metallic encapsulant is preferred if high heat transfer is the criteria, else, plastic containers are most widely used. However, compatibility of both metallic and plastic encapsulants with the PCM needs to be checked. Climator [41] produces rectangular shape pouches of plastic foil integrated with metallic layers. Rubitherm [42] uses rectangular box to encapsulate the PCM. Tin-plated food cans and plastic bottles found to be the cheapest containers for the macroencapsulation.

The manufacturing of microencapsulated PCM is more complex than macroencapsulated PCM as its size falls below 1 mm. However, microencapsulation result in a higher heat transfer rates as compared to that of macroencapsulation [22,31]. This is attributed to a substantially higher surface area to volume ratio, ability to withstand the change in volume during phase change process and less chemical reactivity of PCM with the shell material. Higher heat transfer rate results in rapid melting and solidification of the micro-encapsulated PCM. For macro-capsules, the large capsule size results in temperature differential at the PCM core and boundary. The edge remains solid, whereas, core part may still remain in the liquid form, thus preventing the effective heat transfer [43]. Sari et al. [39] demonstrated that micro-encapsulated PCMs are thermally more reliable and chemically more stable than that of macro-encapsulated PCMs. The only problem with microencapsulated PCM is the possibility of increase in supercooling [33]. Due to supercooling; PCM retains its liquid phase even below its freezing point. The supercooling can be prevented by incorporating nucleating agents [44]. Fan et al. [45] demonstrated that separate addition of 6 wt% sodium chloride and 9 wt% 1-octadecanol in core material resulted in prevention of supercooling, however, the microcapsule surface became rough. Addition of 20 wt% paraffin yielded no supercooling and dispersability. It also resulted in excellent surface finish. Biswas [46] added extra water to reduce the intensity of the supercooling.

There are also studies on the nano-encapsulated PCM for thermal energy storage [47–49]. The advanced technological developments have made it possible to encapsulate the PCM at the nano-scale. Sukhorukov et al. [50] applied the same force on 10 nm and 10 μm size polyelectrolyte capsules and observed that deformation for the 10 nm capsule was substantially smaller as compared to that of 10 μm capsule. This shows that nanocapsules are structurally more stable as compared to macro and micro-capsules and there is a great potential in the use of nanocapsules for thermal energy storage applications. However, the research on nanocapsule is still at the laboratory level. More investigations are required to bring nanocapsules into the commercial applications. The macro and micro-capsules have been successfully commercialized in the market for the TESS applications. Table 1 shows the product details of the industries that are involved in the manufacture of the encapsulated PCMs.

5. Performance improvement of a thermal system using encapsulated PCM

This section provides detailed information on the performance improvement of a thermal system due to incorporation of PCM. Maximum heat transfer between the PCM and heat transfer fluid

Table 1
Manufacturers and their specifications of encapsulated PCMs.

Trademark name/ Industry	PCM (s)	Shell material (s)	Container (s)	Average container size	Application (s)	Reference
Cristopia	Eutectic salts	Polyolefin	Spherical balls	77 mm	Industrial refrigeration, building conditioning	[36]
ClimSel/climator	Sodium acetate, sodium sulphate	–	Pouches	–	Medicine transportation, clothing, air-conditioning, electronic cooling, fire protection	[41]
Rubitherm	Paraffin, salt hydrate in granulate, powder and compound forms	Aluminum, plastic	Box, bag	–	Storage and transport of food, medical equipments, storage materials for textile	[42]
Latest™/ TEAP Energy	Glauber's salt, soda ash, sodium acetate and paraffin wax	Aluminum, steel and polyethylene	Bottles, balls	25.4 mm	Hot pads and solar heating, telecom enclosure, back-up air-conditioning, cold storage	[51]
PCM Products Ltd.	Eutectics, salt hydrates, organic materials, and high temperature salts	Rubber, HDPE plastic	Tube, ball, pouches, plate	40 mm	Space International space station, automotive passive cooling, solar heating and heat recovery	[52]
MPCM/Microtek Laboratories Inc.	Paraffin	polymer	–	17–20 μm	Active wear clothing, woven and non-woven textiles, building materials, packaging, and electronics	[53]
Micronal®/BASF	Paraffin wax	Polymer	Microcapsules impregnated with gypsum wall boards	5 μm	Building conditioning, surface cooling	[54]
DuPont™ Energain™	Paraffin wax	Aluminum	Wall panels	–	Building conditioning, fire protection	[55]
Aegis	Inorganic salts	High density polyethylene	Panels, spherical balls, pouches	75 mm ball dia., 145 mm × 260 -mm size pouch	Cold storage, boilers, solar water heaters, transport of blood, frozen food, fruits and vegetables etc.	[56]

(HTF) or surrounding environment is very essential in order to make a system more compact and efficient [57]. However, most of the PCMs (especially organic PCMs) show a lower thermal conductivity, hence, results in a decreased heat transfer rate. There are numerous studies that explain the techniques for enhancement in heat transfer of PCMs [58–60]. These techniques primarily focus on increasing the thermal conductivity of PCM to improve the system performance. Only a brief overview of these techniques is provided here in the initial part of this section.

Velraj et al. [58] listed heat transfer enhancement techniques for the PCM based applications. It was reported that the heat transfer can be enhanced by the following ways.

1. Using fin configuration.
2. Inserting a high thermal conductivity metal matrix into a PCM.
3. Dispersing the PCM with a high thermal conductivity particles.
4. By micro-encapsulation of the PCMs.

Ettouney et al. [61] observed a three-fold decrease in Fourier number and a three-fold increase in Nusselt number (hence the heat transfer rate) by inserting metal screen/spheres in the paraffin. Sari [62] reported that thermal conductivity of paraffin/high density polyethylene composites can be increased by about 24% by adding 3 wt% expanded and exfoliated graphite. Bellemare [63] reported five methods of applying conductive layer on the encapsulated PCM to improve its thermal and electrical conductivity. These are sputtering, evaporation, chemical vapor deposition, electrochemical and electroless deposition. Out of these, electroless deposition has positively influenced the encapsulated PCM. The applied layer of silver on the micro-encapsulated PCM has substantially improved the thermal and electrical conductivity.

Regin et al. [64] presented a review on the use of PCM capsules for thermal energy storage application. It was reported that the determination of heat transfer during phase change process is complicated due to non-linear operation, change in volume and inadequate knowledge of heat transfer mechanism. The above phenomena found to be the major source of inaccurate prediction of performance of a thermal system. Later, Jegadheeswaran and Pohekar [60] in their review reported that microencapsulation of PCM not only enhances the heat transfer characteristic due to increase in surface area to volume ratio but also alleviates the problems that arises due to change in volume and lower thermal conductivity. It was suggested that there is a need to perform a comparative study of the microencapsulated PCM with the pure PCM to assess its performance. Farid et al. [65] reported that higher heat transfer surface area and the decreased reactivity of the microencapsulated PCM are advantageous for the improvement in thermal performance of a system. Zhao [66] described that microencapsulated PCM has a good potential for thermal energy storage applications. Certain issues that were raised related to the encapsulated PCM are instability, agglomeration and nano size fabrication. It was reported that more research on MPCM based thermal energy storage system is required to reduce the overall cost of the system.

Dutil et al. [67] suggested that effect of micro and nanocapsules on the effective viscosity of the fluid and thermal dilation of PCM needs to be investigated. The use of carbon fiber to improve the thermal conductivity, although it has a poor thermal conductivity was questioned. Prakash et al. [68] during his numerical simulations reported that movement of solid–liquid boundary poses a problem to simulate the phase change process due to lack of knowledge of the movement speed and the two phase mixture. The problem becomes severe if the PCM has more depth, as it takes more time to move the interface boundary from one end to the other. On the other hand, the numerical studies can assume a single phase solution inside the micro-encapsulated PCM and simplifies the problem with a reasonable accuracy. Bony et al. [69] investigated effect of internal convection inside the paraffin that was encapsulated using an aluminum container of dimensions 8.8 cm $\times$ 15 cm $\times$ 0.03 cm. It was observed that temperature fluctuations were increased during the phase change process resulting in increased simulation time.

Talmatsky and Kribus [70] compared effectiveness of PCM based solar water heater with the conventional solar water heater. The PCM was encapsulated inside a small cylindrical container. A number of containers were placed at the top layer of the storage tank. Surprisingly, only a marginal gain in improvement was observed for the PCM based solar water heater. In few cases, even a loss in the performance was observed. Ibanez et al. [71] performed experimental and numerical studies on improvement in heat storage capacity of a solar hot water storage tank using sodium acetate trihydrate encapsulated in aluminum bottles of 8.8 cm diameter and 31.5 cm height. The bottles were placed in the cylindrical water storage tank. It was observed that the total solar fraction was increased from 4% to 8% due to incorporation of encapsulated PCM. The solar fraction represents the contribution of solar energy to the total energy that is to be purchased. Later, it was suggested that merely increase in PCM will not improve the performance. There is a critical value, beyond which addition of PCM will not improve the thermal performance of the system. Cabeza et al. [72] investigated the use of sodium acetate trihydrate encapsulated in a cylindrical aluminum container of size 8.8 cm $\times$ 31.5 cm for thermal energy storage. The energy density as calculated by using sensible heat of water was marked as a baseline case. It was reported that the increase in energy densities for 2, 4 and 6 PCM modules for 1 K temperature difference were 40%, 57.2% and 66.7%, respectively. For 8 K temperature difference they were 6%, 12% and 16.4%, respectively. The temperature of the top layers in the storage tank was warmer than 54 °C for the duration of about 10–12 h. Mehling et al. [73] used PCM modules of size 10 cm $\times$ 30 cm filled with a mixture of PCM–graphite composite. It was observed that the energy density was increased by about 20% to 45%, whereas, the hot water storage period was extended by about 50% to 200%.

Tyagi et al. [74] reported that microencapsulation is one of the best ways of utilizing PCM to maintain the thermal comfort within a building. The microencapsulated PCM can be mixed with either concrete or gypsum wall. This mixture has the ability to reduce the temperature fluctuations especially for the light-weight buildings. Schossig et al. [75] described that micro-encapsulation of PCMs is the easiest way to tackle the problems raised due to macro-encapsulation or direct immersion. The PCM microcapsules can be directly integrated with the building wall. The micro level size of PCM avoids its destruction during drilling the holes in the building wall. Other benefits of micro-encapsulation are high heat transfer rates and better phase change properties. The PCM microcapsules of 8 μm diameter were integrated with the plaster boards. It was observed that, during day time, PCM integrated plaster wall reduced the ambient temperature by 4 K as compared to plaster wall without PCM. The maximum temperature in the PCM room occurred after one hour. During night time, the PCM room temperature was increased to maintain the thermal comfort condition. Subsequently, Cabeza et al. [43] observed a drop of 2 °C for a microencapsulated PCM filled cubicle as compared to conventional cubicle. The PCM used was Micronal PCM (from BASF) with a latent heat of fusion 110 kJ/kg. An improved thermal inertia was observed with the microencapsulated PCM. Castellon et al. [76] carried out similar studies with two different cubicles, one with a mixture of PCM and concrete and other with concrete only. The volume of both cubicles was kept the same. A 4 °C temperature difference was observed between the two cubicles. The peak temperature for the PCM-concrete cubicle

occurred 2 h later than the concrete cubicle. Douglas [77] demonstrated the use of encapsulated paraffin (octadecane) in the floor tile for residential building cooling during day time and heating during night time. It was found that, using micro-encapsulated PCM of 21 μm diameter, the thermal energy storage was about 2.02 MJ/m^2 for a half inch floor tile. Corresponding increase in solar saving and annual cost saving were 17.3% and $100.34, respectively.

Castellon et al. [78] reported that use of micro-encapsulated PCM in a sandwich panel resulted in increased thermal inertia and decreased energy demand for the building construction application. Li et al. [79] used microencapsulated paraffin and a composite mixture of high density polyethylene and wood flour for the latent heat storage. The micro-encapsulation of the PCM prevented it to mix with the composite mixture. The average particle size of the PCM was 7.29 μm. The thermal conductivity of the form-stable PCM was increased by 17.7% by adding 8.8 wt% micro-mist graphite. It was observed that the addition of micro-mist graphite has not deteriorated the mechanical properties of the form-stable PCM. The mechanical test revealed the leak proof characteristics of the molten PCM. The form-stable PCM was found to be thermally stable after subjecting it to 100 melt–freeze cycles. Subsequently, Kenisarin and Kenisarina [80] presented the developments in form-stable PCMs for thermal energy storage applications. The suggested structure supporting materials for the form-stable PCM are high-density polyethylene, styrene–butadiene–styrene triblock copolymer, poly vynil chloride and poly vynil alcohol. The form-stable PCMs represent the solid–solid phase transition materials. It was reported that the form-stable PCMs are free from certain issues, such as, supercooling, instability, high volume change etc. that may incur during solid–liquid phase transition.

Nallussamy et al. [81] reported the use of paraffin encapsulated with a high density polyethylene. The encapsulated spherical capsule has a diameter of 55 mm and thickness of 0.8 mm. The 264 capsules occupied about 50% of the storage tank space. It was observed that batch wise discharge of water with combined energy storage system (sensible heat + latent heat) resulted in fast charging period as compared to continuous discharge with only sensible heat storage. Esen et al. [82] numerically investigated two cases, first, PCM packed in the cylinder with a parallel fluid flow over it (mode 1) and second, the fluid flows through cylinder that is immersed in the PCM (mode 2). Between these two, mode 2 found to be the best heat transfer mechanism resulting in a substantially reduced melting time for the PCM. Kousksou [83] reported that efficiency of a thermal storage system can be improved by arranging the layers of spherical capsules containing different PCMs in a particular order. The PCMs used were PCM28, PCM30 and PCM32 encapsulated in a 60 mm spherical capsule and placed in a cylindrical tank of height 1.5 m. PCM28, PCM30 and PCM32 represent the PCMs with the melting point of 28 °C, 30 °C and 32 °C, respectively. Two cases were studied; (i) PCM28, PCM30 and PCM32 arranged in equal layers in the order of bottom to top of the tank and (ii) the reverse order as given in (i). In the former case, the PCM32 placed in the top layer could not melt, however, in the latter case, the PCM28 placed in the top layer was successfully melted. Hence, thermal performance with the latter case was improved by restructuring the layers of the PCMs.

Song et al. [84] demonstrated an increase in wall strength of the microencapsulated bromo-hexadecane due to addition of silver nano-particles. The thermal and structural stability of PCM microcapsules incorporated with silver nano-particles was substantially higher as compared to conventional PCM microcapsules. This was attributed to the increase in strength and toughness due to addition of silver nano-particles. Davis et al. [85] used macrocapsules containing plurality of microcapsules suspended in a gelling agent for the thermal energy storage applications, especially, thermal comfort using coat or vest. Melamine–formaldehyde was used as a shell material for micro-encapsulation of octadecane. The microcapsule size was varied from 2 μm to 40 μm, whereas, macrocapsule size was in the range of 1 mm to 10 mm. Ma et al. [86] used microcapsules of size 0.5–2 μm containing paraffin as a PCM. The encapsulation was carried out with PMMA. It was reported that microencapsulated PCM has good potential for thermal energy storage applications. A good thermal reliability was observed as the phase change properties were marginally changed even after 1000 thermal cycles.

Zhang et al. [87] performed experiments on *n*-octadecane micro-encapsulated with urea–melamine–formaldehyde with different mole ratios to assess its phase change properties and thermal stability. The best performance was achieved at mole ratios of urea–melamine–formaldehyde in the order of 0.2:0.8:3 that resulted in enhanced thermal stability up to 163 °C. The stability was further increased up to 200 °C by adding cyclohexane. Later, Salaun et al. [88] demonstrated the effect of ratio of formaldehyde/melamine (F/M) on the mechanical properties of paraffin encapsulated with amino resin. It was reported that a lower F/M ratio results in a smooth encapsulation surface with a significant reduction in the structural strength of the microcapsule. Conversely, at higher F/M ratio, better mechanical properties of the encapsulated PCM were observed.

6. Effect of core-to-coating ratio

Core-to-coating ratio is a critical parameter that decides the mechanical strength of the encapsulated PCM. A lower core-to-coating ratio leads to excessive shell thickness, which in turn reduces the amount of PCM contained, whereas, the encapsulated PCM strength deteriorates and the chances of PCM spillage increases for a higher core-to-coating ratio. A review of effect of core-to-coating ratio on the structural and thermal stability of the encapsulated PCM is given here in detail.

Su et al. [89] investigated effect of various core-to-shell mass ratios on the performance of an encapsulated PCM. Lauryl alcohol and melamine–formaldehyde resin were used as core and shell materials, respectively. The encapsulated PCM diameter was in the range of 5–10 μm. The core-to-shell mass ratio was varied from 1:1 to 4:1 in the step of 1:1. It was reported that higher core material is always essential to store and release more thermal energy. However, for a higher core size, a decreased shell thickness can adversely affect the mechanical properties of the encapsulated PCM. The core-to-shell mass ratio of 3:1 was found to be the optimum. It was also observed that the mechanical properties of double-shell micro-encapsulated PCM were excellent as compared to that of single-shell. Subsequently, Hawlader et al. [31] reported that a lower coating thickness results in poor performance of a micro-encapsulated PCM. A higher core-to-coating ratio leads to an increased micro-encapsulation efficiency and hence, rapid storage and release of thermal energy.

Ohtsubo et al. [90] investigated breaking behavior of the microcapsule based on the mass mean diameter (D) and wall thickness (T). The capsule was microencapsulated with polypropylene. It was reported that at large (D/T) ratio, a small force is enough to break the 50% of the microcapsule. Roy and Sengupta [91] performed experimental studies on micro-encapsulated PCMs for the higher heat transfer rates. Two PCMs under study were *n*-eicosane and stearic acid with two different shell thicknesses of 15% and 30% of the total microcapsule volume. The structural and thermal stability of microcapsules were investigated using thermal cycling and radiation test. It was observed that the PCM with lower shell thickness (15% of the total microcapsule volume) failed to sustain the repeated thermal

cycles through melting point. However, microcapsules with higher shell thickness found to be structurally and thermally sound for at least 100 cycles. Zhang and Wang [40] performed microencapsulation of *n*-octadecane using polyurea as a shell material. The investigations were carried out at different core-to-shell weight ratios of 70/30 and 75/25. The mean particle sizes at these two core-to-shell ratio were 6.9 μm and 7.1 μm, respectively. For a higher core-to-coating ratio (i.e., 75/25), an early spillage of the PCM was observed at a temperature of about 200 °C. A better thermal stability of microencapsulated PCM with a lower core-to-coating ratio was observed. The microcapsule synthesized using Jeffamine resulted in higher encapsulation efficiency and better phase change properties as compared to synthesized using ethylene diamine and diethylene triamine.

Wei et al. [92] investigated the effect of PCM diameter (2 mm, 3 mm, 4 mm and 5 mm) on the heat transfer characteristics. A rapid heat release was observed for the smallest PCM diameter (i.e., 2 mm), and gradually decreased with increase in diameter. This was attributed to the high surface area to volume ratio of the small diameter encapsulated PCM. The effect of shell thickness (0.2 mm and 0.4 mm thickness) on heat release showed that a higher shell thickness resulted in modestly improved capsule performance. However, due to increased shell thickness, the amount of core material reduces and hence affects the heat storage capacity. In contrast to the results of Wei [92], Ettouney et al. [93] observed that increase in diameter and number of beads placed inside a spherical capsule result in enhanced heat transfer characteristics. Materials used for the spherical capsule and bead were copper and stainless steel, respectively. The spherical capsule diameter was kept at 30 mm and bead diameters were varied to 4 mm, 5 mm and 6 mm.

An overview of key parameters of encapsulated PCM as used by various researchers and their result is shown in Table 2.

7. Effect of shell material

Shell material plays an important role in deciding the heat transfer characteristics as well as mechanical strength of the encapsulated PCM. A high strength shell material with good thermal characteristics not only improves the performance of a system but also increases the number of thermal cycles that the encapsulated PCM withstands.

An ideal shell material should have following properties:

1. It should have sufficient structural and thermal strength to withstand the phase change process of PCM.
2. It should retain all the thermophysical properties at the micro and nano-level size.
3. It should be leak proof.
4. It should not react with the enclosed PCM.
5. It should be a good water diffusion barrier.
6. It should have higher thermal conductivity to ease the heat exchange between the PCM and its surrounding.

Common materials that can be used for encapsulation are polypropylene, polyolefin, polyamide, silica, polyurea, urea–formaldehyde, copper, aluminum etc. A survey on effect of shell material on the heat transfer characteristics is presented below.

Werner [95] performed experiments on thermal energy storage using a phase change mixture of 90% myristic and 10% lauric acid. Three different shell materials, namely, polypropylene, polyethylene and polyamide were used during the experiment. It was observed that first two containers (polypropylene and polyethylene) showed diffusion with paraffin, whereas, there was no chemical reaction between the PCM and the polyamide. It was also reported that encapsulation of organic PCM is more difficult than inorganic PCM. This was attributed to the similar structure of the organic PCM and the plastic container that leads to a diffusion or initiation of chemical reaction. Sun and Zhang [96] investigated effect of different coating materials, namely, melamine–formaldehyde, urea–formaldehyde and gelatin on the mechanical strength of the microcapsule. It was observed that melamine–formaldehyde and urea–formaldehyde ruptured under the compression test, whereas, gelatin was found to be structurally stable. The gelatin capsule was elastic up to the deformation of 50%.

Zhang et al. [40] demonstrated that polyurea has good physical properties and chemical stability. It is also completely insoluble in water and other solvents. Therefore, it was reported that polyurea has a great potential to become one of the best shell material for

Table 2
Summary of major encapsulation parameters as used during various investigations.

Sr. no.	PCM	Method	Type	Coating material	Capsule wall thickness	Capsule size	Remark	Refer-ence
1.	*n*-Octacosane	Emulsion polymerization	Micro	Polymethyl methacrylate (PMMA)	–	0.25 μm	Good energy storage potential	[39]
2.	*n*-octadecane	Interfacial polycondensation	Micro	Polyurea shell	–	Core/shell ratio (wt:wt) = 70:30	High encapsulation efficiency	[40]
3.	Octadecane	–	Micro	Polyester	–	21 μm	Annual saving increased by 24%	[77]
4.	Bromo-hexadecane	Polymerization technique	Nano	Silver nano-particles	40–60 nm	core/shell ratio = 5:1	High thermal and structural stability of PCM due to addition of silver nano-particles	[84]
5.	*n*-octadecane	In situ polymerization	Micro	Urea—melamine—formaldehyde	Core/shell ratio (wt:wt) = 78:22	0.2–5.6 μm	Thermal stability enhanced by 10 °C	[87]
6.	*n*-eicosane and stearic acid	–	Micro	Cross-linked polyvinyl alcohol	15–30%	50 μm–250 μm	Thicker wall resulted in good thermal and structural stability	[91]
7.	Paraffin wax	–	Macro	Stainless steel	0.4 mm	2 mm	Spherical shape resulted in highest heat transfer rate	[92]
8.	Paraffin	Injection or blowing process	–	Polyethylene terephthalate (PET)	–	–	PET shell performed better compared to polyolefin and polycarbonate	[94]

the microencapsulation of the PCMs. In the subsequent studies, Zhang et al. [38] reported that silica posses a substantially higher thermal conductivity of 1.296 W/m-K as compared to polymeric materials ($k=0.2$ W/m K). The phase change properties, thermal conductivity, encapsulation efficiency and antiosmosis properties were significantly enhanced due to micro-encapsulation of octadecane with the silica shell. The encapsulation with silica has improved the thermal conductivity from 0.1505 W/m K to 0.6213 W/m K. Later, Fang et al. [34] as well reported that silica has excellent physical properties to be qualified as a good shell material. It has good chemical and thermal stability, significantly higher thermal conductivity and high storage capacity. The silica shell provides sufficient mechanical strength and prevents leakage of the molten PCM. The difference between melting and solidifying temperature was found to be marginal for the silica encapsulated paraffin as compared to paraffin. This was attributed to the silica shell that acts as a nucleating agent.

Alkan et al. [29] carried out experiments on preparation, characterization and thermal analysis of microencapsulated docosane with PMMA as a coating material. After 1000, 3000 and 5000 thermal cycles, a substantially improved thermal reliability was observed in terms of change in temperature and enthalpy. Garcia et al. [26] assessed thermal stability of microcapsules synthesized by different shell compositions, namely, Sterilized Gelatine/Arabic Gum (SG/AG) and Agar-Agar/Arabic Gum (AA/AG). The results of Thermogravimetric analyses showed that the microcapsules decomposed in a more gradual manner for the AA/AG method, whereas, for the SG/AG method, the microcapsules break and decomposed at the same time. Hatfield [97] used polyurethane-urea to encapsulate polyethylene glycol 8000 using interfacial polymerization. It was reported that the shell material must be elastomeric to accommodate the change in volume during the phase change process. A minimal loss in latent heat of fusion was observed due to encapsulation of the PCM.

Although melamine–formaldehyde and urea–formaldehyde are one of the most commonly used shell materials, the health and environmental hazard issues have been observed due to emission of formaldehyde [29,34]. Therefore, the recent trend is inclined towards the use of formaldehyde-free shell materials. Zhang et al. [38] suggested that use of combination of organic–inorganic materials as a shell material can be an optimistic choice. Organic material offers structural flexibility and easier processing, whereas, inorganic materials are well known for good chemical and thermal stability, excellent flame retardancy, higher structural strength and substantially higher thermal conductivity. Jegadheeswaran and Pohekar [60] suggested the use of low density high thermal conductivity additives, such as carbon fibers, that have lower weight, excellent corrosion resistance, compatibility with most of the PCMs and thermal conductivity almost equal to that of aluminum and copper.

8. Effect of encapsulation geometry

It is observed that encapsulation geometry has substantial effect on the heat transfer characteristics of the PCM. A brief description of commonly used encapsulation geometries is given in Section 4 (see Fig. 3). A survey of effect of various encapsulation geometries on the heat transfer characteristics is provided below.

Wei et al. [92] performed numerical and experimental studies on various geometries of encapsulated PCMs, namely, sphere, cylinder, plate and tube to improve the heat transfer rate. It was reported that the spherical shape resulted in the highest heat transfer rate. For other geometries, the heat transfer rate decreased in the order of cylinder, plate and tube. Zhang et al. [98] described the application of microtubule PCMs for thermal energy storage. The microcapsules were stored in the microtubule of length 0.1–50 mm and diameter 0.1–1000 μm, encapsulated using polymer. It was reported that due to high hollowness and micro-size diameter, the microtubules can efficiently and rapidly transfers the heat. Agyenim et al. [19] reported that cylindrical and rectangular shapes are the most commonly used container shapes for the enhanced heat transfer between the PCM and HTF. A shell and tube arrangement found to give the minimal heat loss. Darkwa and Su [99] performed simulation studies on the thermal performance of a microencapsulated PCM board by varying the encapsulation geometry (rectangular, triangular and pyramidal). It was observed that the thermal response time for the rectangular and triangular geometries were half that of pyramidal geometry. The microencapsulation resulted in ten times increase in thermal conductivity as compared to that of pure PCM. However, the energy storage density was reduced by about 48%.

9. Melting and solidification of PCM

Performance of a PCM based thermal system is significantly affected by the melting and solidification characteristics of the PCM. Depending upon the geometry and the flow and heat transfer characteristics, one or more dimensionless parameters amongst Nusselt number (*Nu*), Rayleigh number (*Ra*), Stefan number (*Ste*) and Grashof number (*Gr*) may play an important role during the phase change process. The Stefan number is the ratio of sensible heat to the latent heat of the PCM as given by the following equation.

$$Ste = \frac{C_P(T_f - T_0)}{\Delta H} \tag{3}$$

For higher melting rate a lower Stefan number is desirable, whereas, a higher Stefan number can improve the solidification rate.

Accurate prediction of the flow and heat transfer characteristics during melting and solidification of PCM is a very complicated task due to moving interface boundary. The speed of this boundary is not known a priori. Josef Stefan was the first who reported this problem, hence, it is also known as the 'Stefan problem' or the moving boundary problem [100]. Analytical solution for this problem is available only for one-dimensional case with very simplified boundary conditions. The unknown speed of the solid–liquid boundary and the highly non-linear phase change characteristics makes it difficult to achieve the analytical solution for the complex cases. However, numerical methods can be used with a reasonable accuracy to tackle the above challenges. Teng and Akin [101] explained that enthalpy and capacity are the two most commonly used fixed domain methods to deal with such problems.

For proper functioning of a PCM based thermal system, rapid melting and solidification of the PCM is always desirable. The variation of thermophysical properties during melting and solidification depends upon the PCM chosen. The thermophysical properties can be assumed to be independent of temperature but different for solid and liquid phases [102,103]. Dwarka and Kim [104] considered the constant thermophysical properties during phase change process except the specific heat. Long [105] assumed constant thermophysical properties during phase change process. The effect of natural convection in the liquid phase was neglected. This section provides a survey on the effect of mass flow rate of HTF, inlet and initial temperature of HTF, various shell materials and container shapes on the flow and heat transfer characteristics of the PCM during the solidification and melt processes.

Veerappan et al. [106] analyzed the effect of encapsulation size, initial PCM temperature and external fluid temperature on

the solidification time. The encapsulated PCM diameter was varied from 4 cm to 12 cm. It was observed that a large size PCM requires more time to solidify and vice versa. The initial temperature found to have negligible effect on the solidification time. Wu et al. [107] observed that inlet temperature of HTF, porosity of packed bed and flow rate of HTF have a significant influence on the complete solidification and melting time than the effect of capsule diameter of the PCM. A higher HTF inlet temperature resulted in substantially reduced melting time, whereas, higher HTF flow rate and higher porosity of packed bed led to a substantial decrease in the solidification and melting time. Arkar and Medved [108] reported that heat capacity of a PCM is a function of temperature. A significant change in specific heat was observed during the phase change process. An apparent heat capacity for the PCM is given by the following equation.

$$C_{app}(T)=\frac{q(T)}{m_{PCM}\theta}+C_p \tag{4}$$

Zukowski [109] formulated a mathematical model of thermal energy storage for heating application wherein a specific heat capacity approach was proposed to simulate the model for solidification and melting process. The natural convection during melt process was simulated using equivalent thermal conductivity as given by the following equation.

$$\frac{k_{eq,p}}{k_p}=CRa^n\left(\frac{\delta}{l}\right)^m \tag{5}$$

It was observed that the charge cycle time was higher than the twice as that of discharge cycle. Zivkovic and Fujii [110] performed computational and experimental investigations to determine the effect of encapsulating container shape on the melting time of calcium chloride hexahydrate. The model assumed negligible effects of conduction in the direction of HTF and natural convection in the molten PCM. The containers were rectangular (100 mm × 100 mm × 20 mm) and cylindrical, both made of stainless steel. In order to compare, the volume and heat transfer area of both of the containers were kept equal. A marginal difference in melting time was observed at smaller volume. However, at large volume, the rectangular container has halved the melting time of PCM as compared to that of cylindrical container.

Zalba et al. [3] demonstrated the use of PCM for free-cooling of building. It was observed that the thickness of encapsulation, inlet air temperature and air flow have significant influence on the solidification process, whereas, during melting process, the inlet air temperature showed more influence as compared to the encapsulation thickness. Kalaiselvam et al. [111] analytically and experimentally studied the solidification and melting characteristics of a PCM (60% *n*-tetradecane + 40% *n*-hexadecane) encapsulated in a copper cylinder of size 70 mm × 350 mm × 1 mm. It was reported that solidification and melting processes are dominated by conduction and natural convection, respectively. The solidification time depends upon Stefan number and heat generation parameter (β), whereas, melting time is a function of equivalent thermal conductivity.

The heat generation parameter is given by:

$$\beta=\frac{\dot{q}R^2}{k(T_0-T_f)} \tag{6}$$

The presence of heat generation within the encapsulated PCM significantly increases the solidification time and accelerates the melting process. It was also observed that increasing the capsule radius substantially rises the complete solidification time. This is attributed to the rise in heat generation parameter due to increase in radius of the cylinder as evident from Eq. (6).

Stritih [112] performed experimental studies on solidification and melting characteristics of paraffin (Rubitherm RT 30) inside a rectangular container of size 650 mm × 500 mm × 120 mm. The heat transfer correlations for solidification and melting are given respectively as follows.

$$Nu_s=7\times10^{-13}Ra^{0.9364} \tag{7}$$

$$Nu_m=8\times10^{-12}Ra^{1.0392} \tag{8}$$

From above equations, it can be observed that natural convection during melting is almost ten times higher than that during solidification. Subsequently, Tan et al. [113] computationally and experimentally demonstrated that the conductive heat transfer was dominant in the initial stage of the phase change process. However, with the progress in melting process, natural convection became dominant. Ettouney et al. [114] observed that natural convection was dominant during melting for upward flow of HTF, whereas, for downward flow, the natural convection was negligible. The solidification process found to be dominated by conduction and independent of flow direction of HTF. Cho and Choi [115] reported the phase change characteristics of paraffin (40% *n*-tetradecane and 60% *n*-hexadecane) during melting and solidification and compared it to water. The spherical capsule had a high-density polyethylene shell with a diameter of 24.5 mm and thickness of 0.8 mm. The spherical capsules were piled up in seven layers. A shorter melting time was observed for the first layer placed near the edge of the storage tank. This was attributed to the lower porosity at the center of the tank that results in reduced heat transfer rates. The effect of increased inlet temperature showed that the phase change period during solidification was significantly higher than that of melting process. In contrast, Zukowski et al. [116] in their first ever attempt to use paraffin wax (RT-56) encapsulated with the polyethylene bag observed that the charging period was substantially long, whereas, discharge period (cooling process) was significantly reduced.

Ismail and Henriquez [117] performed a detailed study on the effect of shell material, shell thickness, capsule diameter and initial PCM temperature on the total solidification time of the PCM. The results are shown in Table 3. It was observed that a shell material with high thermal conductivity, smaller capsule size and lower external surface temperature results in reduced time for the complete solidification. The critical radius for copper, PVC and glass for a fixed capsule diameter of 0.05 m were found to be 17.46 m, 0.003 m and 0.054 m, respectively. Increasing the capsule radius until the critical radius increases the heat transfer rate, hence,

Table 3
Effect of various parameters on the solidification time of PCM [117].

Shell material	Copper	Stainless steel	Teflon	PVC
Solidification time	Short	Short	Large	Largest
Capsule diameter (mm)	20	100	200	400
Solidification time	Shortest	Short	Large	Largest
External surface temperature (°C)	−5	−10	−20	–
Solidification time	Shortest	Short	Large	–

Table 4
Melting time for various shell materials as observed by Ismail and Henriquez [118].

Shell material	Copper	Aluminum	Polyethylene	Acrylic	PVC
Melting time (h)	7	7	8	9	9.3

decreases the time required for the solidification. Therefore, heat transfer rate can be increased by increasing the diameter of copper and glass capsules. However, for PVC, as the critical radius was less than the capsule size of 0.05 m, any increase in capsule size would have decreased the heat transfer rate. Later, Ismail and Henriquez [118] demonstrated effect of various shell materials, namely, copper, aluminum, acrylic, PVC and polyethylene on the solidification and melting time of PCM encapsulated in a 77 mm diameter spherical capsule of thickness 2 mm. The spherical capsule contained water and ethylene glycol of 30% volumetric concentration. Copper and aluminum shells resulted in the shortest time for the melting of the PCM. Table 4 shows the melting time for all the shell materials. The melting time required for polyethylene was modestly good, whereas, PVC experienced a longer melting time of about 9.3 h. It was also observed that with decrease in working fluid entry temperature, there was a significant reduction in time required for both charging and discharging process. Similar studies were carried out by Ismail and Moraes [119] using a mixture of water–glycol as a PCM. It was reported that a higher thermal conductivity of the shell material, smaller capsule size and lower HTF temperature reduces the total solidification time.

Akgun et al. [120] investigated effects of mass flow rate and HTF temperature on the solidification and melting characteristics of paraffin in a tube in shell heat exchanger. It was observed that the increase in HTF temperature results in increased solidification time. The effect of HTF mass flow rate found to be negligible at the tube inlet. However, far upstream from the tube inlet, the increase in HTF mass flow rate showed higher HTF temperature and hence the reduced melting time. Subsequently, Regin et al. [121] as well reported that increase in HTF temperature and mass flow rate resulted in the lower melting time. The paraffin wax was used as a PCM contained within the spherical capsule. The investigations performed with various capsule diameters showed the substantially reduced melting and solidification time for smaller diameter capsules as compared to that of large diameter. Due to lower heat transfer coefficient during solidification process, the time required for complete solidification was significantly higher as compared to that of melting process. The above results found to be in line with the measurements of Wu and Fang [122].

10. Microencapsulated phase change slurry (MPCS)

The encapsulated phase change material can be dispersed in the HTF (commonly water) to increase the heat transfer rate. PCM can then be pumped back to store or release the thermal energy. Such a mixture of encapsulated PCM and HTF is termed as the phase change slurry (PCS). The mixture is termed as the microencapsulated phase change slurry (MPCS) in case the encapsulation is at the micro level. The MPCS not only acts as an energy storage device but also as a heat transport system. Due to this, MPCS is commonly used in secondary loop heat transfer systems such as the refrigeration system. The suspended microcapsules store and transport large amount of thermal energy as compared to microcapsules that are not in direct contact with the HTF.

Substantial investigations have been carried out to determine the heat and fluid flow characteristics of the PCS [123–129]. Charunyakorn et al. [130] for the first time reported that there is a great potential in the PCS in terms of increase in heat transfer rate. The Nusselt number for PCS varies from 1.5 to 4 times the Nusselt number for single phase fluid. The MPCS can be analyzed as a lumped system if the Biot number is less than 0.1. For this, there should be negligible resistance to the conduction as compared to resistance to the heat transfer between MPCS system and the surrounding [131]. Chen and Fang [132] presented a review on heat transfer characteristics of MPCS flowing in a horizontal circular tube. It was reported that the heat transfer rate of the MPCS increases with reduction in supercooling and increase in mass fraction and the Reynolds number of the slurry. Zhang et al. [133] reported that thermophysical properties of MPCS play an important role in the heat transfer process. It was suggested to add certain amount of nano-particles to improve the thermal conductivity of the MPCS. In order to treat the slurry as the Newtonian fluid, it was recommended that the total volume fraction of the MPCS should fall below 25%. Beyond certain limit, the increased volumetric concentration of the MPCS results in rapid increase in viscosity, pressure drop and decrease in convective heat transfer [127,134]. Choi et al. [128] observed that melting of PCS particles resulted in substantial reduction in local pressure drop and significant variation in local heat transfer coefficient from inlet to outlet. Alvarado et al. [135] showed an increase in heat storage capacity of MPCS even at low mass fractions. The microcapsules found to be durable when smaller than 10 μm. Yang et al. [136] provided MPCS and phase change emulsion as two kinds of HTFs. It was demonstrated that encapsulation of tetradecane with polymethyl methacrylate (PMMA) and polyethyl methacrylate (PEMA) resulted in better heat storage capacity as compared to polystyrene.

Zeng et al. [129] reported that during phase change process, Stefan number (*Ste*) and dimensionless phase change temperature range (*Mr*) are the two most important parameters that influence the Nusselt number fluctuation. It was observed that the Nusselt number fluctuation increases with decrease in both *Ste* and *Mr*. Wang et al. [137] proposed a new correlation for predicting local heat transfer coefficient for laminar MPCS. An increase in slurry particle fraction resulted in the improvement in local Nusselt number. The local heat transfer coefficient for MPCS was higher than that of pure water. Chen et al. [138] reported that using MPCS, the improvement in effective specific heat and heat transfer rate were 28.1% and 23.6%, respectively. As compared to water, the saving in pumping cost was about 67.5% due to increased heat transfer rate. Zhang et al. [139] investigated natural convection heat transfer characteristics of microencapsulated PCM in a rectangular heat storage tank. An easier initiation of the natural convection was observed at higher mass concentration of the slurry. A local maximum heat transfer coefficient was observed during the phase change process.

Hu and Zhang [140] proposed a modified form of conventional Nusselt number correlation for laminar flow MPCS in a circular tube with constant heat flux. It was demonstrated that Stefan number and volumetric concentration of microcapsules are the most influencing parameters on the heat transfer enhancement of MPCS. Along with these, initial supercooling, phase change temperature range and microcapsule diameter also found to have considerable effects on the heat transfer enhancement. Sabbah et al. [141] showed that for a micro-channel heat sink, a significantly higher heat transfer coefficient can be obtained by using MPCS instead of water only. The low concentration high velocity slurry resulted in better heat transfer rates. Zhang et al. [142] carried out experimental studies on MPCS in a horizontal rectangular enclosure heated from the bottom. It was observed that an increase in mass concentration of the slurry improved the heat storage capacity and the completion time of heat storage. Rapid heat storage and high heat transfer coefficient were observed only in the beginning of the heating process. This is

attributed to a substantially higher temperature difference between the HTF and the MPCS in the beginning of the heating process.

11. Challenges for designing an encapsulated PCM based thermal system

The major challenges that may arise while designing the encapsulated PCM based thermal system are addressed here as given below.

- One of the major obstacles for the commercialization of an encapsulated PCM based system is the high cost of encapsulation. This increases the overall cost of the system.
- The correct choice of PCM, shell material, encapsulation preparation method and its size varies according to the application.
- Precise prediction of moving solid–liquid boundary during the phase change process is still a major problem to be resolved. The rate of movement of this boundary is not known a priori.
- Another important parameter to consider while designing the encapsulated PCM based thermal system is the reduction in PCM effectiveness over the number of thermal cycles. After attaining a certain number of thermal cycles, the thermophysical properties of the PCM deteriorates substantially leading to a significant reduction in structural and thermal stability of the PCM. This results in a decreased system performance.
- For proper functioning of a PCM based TESS, the repetition of charge and discharge cycles are significantly important. The functioning of the system may disrupt in case the discharged PCM could not be charged. This is likely to occur for the PCM based TESS working on natural resources such as solar water heater, solar space heater etc.
- For MPCS, the conventional heat transfer correlations cannot be used due to increased pressure drop and increased viscosity of the slurry. An in-depth knowledge of heat transfer enhancement mechanism is essential while designing the MPCS based thermal system.
- Manufacture of microencapsulated PCM with a metallic shell material is still an unresolved problem.
- Other considerable challenges are phase segregation and supercooling of the PCM. The inorganic PCMs are observed to be more prone for these challenges. Although these problems can be alleviated by addition of suitable enhancement materials, the impact due to addition of these materials on the latent heat storage capacity and phase change temperature of the PCM is evident.

12. Conclusions

This paper presents a thorough survey on the effect of PCM encapsulation parameters on the flow and heat transfer characteristics as well as structural and thermal stabilities of an encapsulated PCM. The major findings of this survey are listed as given below.

1. The core-to-coating ratio found to be a critical parameter that decides the mechanical and thermal stability of the encapsulated PCM. A higher core-to-coating ratio results in a weak shell, whereas, lower core-to-coating ratio reduces the amount of PCM contained, hence, decreases the heat storage and release capacity.
2. Thermal conductivity of shell material plays an important role in the heat exchange between the PCM and the HTF. For higher heat transfer rates, a metallic shell material like copper, aluminum or steel can be a good choice. The metallic shell materials can also be useful for high temperature PCM applications. However, their microencapsulation is a challenge.
3. For organic PCMs, the inorganic shell materials can be a good choice due to their excellent thermal conductivity, high mechanical strength and good diffusion barrier characteristics. Silica exhibits the above mentioned properties and has a great potential to become a good shell material.
4. Thermal and structural stability of the microcapsules found to be substantially improved due to addition of silver nanoparticles. The mechanism for this improvement was attributed to the increased thermal conductivity, toughness and strength due to distribution of silver nano-particles on the shell surface.
5. The solidification and melting processes are dominated by conduction and natural convection, respectively. A high thermal conductivity, smaller capsule diameter and lower external surface temperature reduce the total solidification time of the encapsulated PCM.
6. It was observed that the Stefan number, volumetric concentration of microcapsule, phase change temperature range and capsule diameter have significant influence on the heat transfer enhancement of MPCS. Beyond certain limit, the increase in volumetric concentration of the microcapsule leads to a substantial increase in pressure drop and viscosity and decrease in convective heat transfer rate.

Long-term durability while being pumped and being constantly cooled and heated needs to be experimentally shown for MPCS before a broad industrial adoption.

Acknowledgment

Authors would like to thank Dr. Andrey Soukhojak and Dr. David Bank (both from The Dow Chemical Company, Midland, USA) for their in-depth review and valuable suggestions for the improvement of this manuscript.

References

[1] Kyle JA. Material for protecting sheets, &c., in tinning. US Patent 1901; No. 679,972.
[2] Kuznik F, David D, Johannes K, Roux J. A review on phase change materials integrated in building walls. Renewable and Sustainable Energy Reviews 2011;15(1):379–91.
[3] Zalba B, Marn JM, Cabeza LF, Mehling H. Free-cooling of buildings with phase change materials. International Journal of Refrigeration 2004;27: 839–49.
[4] Pasupathy A, Velraja R, Seeniraj RV. Phase change material-based building architecture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews 2008;12:39–64.
[5] Antony VAR, Velraj R. Review on free cooling of buildings using phase change materials. Renewable and Sustainable Energy Reviews 2010;14:2819–29.
[6] Kandasamy R, Wang XQ, Mujumdar AS. Application of phase change materials in thermal management of electronics. Applied Thermal Engineering 2007;27:2822–32.
[7] Tan FL, Tso CP. Cooling of mobile electronic devices using phase change materials. Applied Thermal Engineering 2004;24:159–69.
[8] Lu TJ. Thermal management of high power electronics with phase change cooling. International Journal of Heat and Mass Transfer 2000;43:2245–56.
[9] Yagi J, Akiyama T. Storage of thermal energy for effective use of waste heat from industries. Journal of Materials Processing Technology 1995;48: 793–804.
[10] Nomura T, Okinaka N, Akiyama T. Waste heat transportation system, using phase change material (PCM) from steelworks to chemical plant. Resources, Conservation and Recycling 2010;54:1000–6.
[11] Mondal S. Phase change materials for smart textiles—an overview. Applied Thermal Engineering 2008;28:1536–50.
[12] Gin B, Farid MM. The use of PCM panels to improve storage condition of frozen food. Journal of Food Engineering 2010;100:372–6.
[13] Martin V, He B, Setterwall F. Direct contact PCM–water cold storage. Applied Energy 2010;87:2652–9.

[14] Fath HES. Technical assessment of solar thermal energy storage technologies. Renewable Energy 1998;14(1–4):35–40.
[15] Shukla A, Buddhi D, Sawhney RL. Solar water heaters with phase change material thermal energy storage medium: a review. Renewable and Sustainable Energy Reviews 2009;13:2119–25.
[16] Mettawee EBS. Assassa GMR. Experimental study of a compact PCM solar collector. Energy 2006;31:2958–68.
[17] Sokolov M, Keizman Y. Performance indicators for solar pipes with phase change storage. Solar Energy 1991;47(5):339–46.
[18] Sarier N, Onder E. The manufacture of microencapsulated phase change materials suitable for the design of thermally enhanced fabrics. Thermochimica Acta 2007;452:149–60.
[19] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews 2010;14:615–28.
[20] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009;13:318–45.
[21] Zhu N, Ma Z, Wang S. Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Conversion and Management 2009;50:3169–81.
[22] Khudhair AM, Farid MM. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. Energy Conversion and Management 2004;45:263–75.
[23] Xi L, Zhang P, Wang RZ. Preparation and thermal characterization of expanded graphite/paraffin composite phase change material. Carbon 2010;48:2538–48.
[24] Song G, Ma S, Tang G, Yin Z, Wang X. Preparation and characterization of flame retardant form-stable phase change materials composed by EPDM, paraffin and nano magnesium hydroxide. Energy 2010;35:2179–83.
[25] Xi P, Gu X, Cheng B, Wang Y. Preparation and characterization of a novel polymeric based solid–solid phase change heat storage material. Energy Conversion and Management 2009;50:1522–8.
[26] Garcia LB, Ventol L, Cordobilla R, Benages R, Calvet T, Cuevas-Diarte MA. Phase change materials (PCM) microcapsules with different shell compositions: preparation, characterization and thermal stability. Solar Energy Materials & Solar Cells 2010;94:1235–40.
[27] Li W, Zhang XX, Wang XC, Niu JJ. Preparation and characterization of microencapsulated phase change material with low remnant formaldehyde content. Materials Chemistry and Physics 2007;106:437–42.
[28] Sari A, Alkan C, Karaipekli A, Onal A. Preparation, characterization and thermal properties of styrene maleic anhydride copolymer (SMA)/fatty acid composites as form stable phase change materials. Energy Conversion and Management 2008;49:373–80.
[29] Alkan C, Sari A, Karaipekli A, Uzun O. Preparation, characterization, and thermal properties of microencapsulated phase change material for thermal energy storage. Solar Energy Materials & Solar Cells 2009;93:143–7.
[30] Green KB. Carbonless paper production. Ohio: NCR Corporation; 1953.
[31] Hawlader MNA, Uddin MS, Khin MM. Microencapsulated PCM thermal-energy storage system. Applied Energy 2003;74:195–202.
[32] Jahns E. Microencapsulated phase change material. Technical report, BASF, Germany.
[33] Mehling H, Cabeza LF. Heat and cold storage with PCM—an up to date introduction into basics and applications. Springer; 978-3-540-68556-2.
[34] Fang G, Chen Z, Li H. Synthesis and properties of microencapsulated paraffin composites with SiO_2 shell as thermal energy storage materials. Chemical Engineering Journal 2010;163(1-2):154–9.
[35] Hart RL, Work DE Flame resistant microencapsulated phase change materials. US Patent 1995;No. 5,435,376.
[36] 〈www.cristopia.com〉.
[37] Jin Z, Wang Y, Liu J, Yang Z. Synthesis and properties of paraffin capsules as phase change materials. Polymer 2008;49:2903–10.
[38] Zhang H, Wang X, Wu D. Silica encapsulation of *n*-octadecane via sol–gel process: a novel microencapsulated phase-change material with enhanced thermal conductivity and performance. Journal of Colloid and Interface Science 2010;343:246–55.
[39] Sari A, Alkan C, Karaipekli A, Uzun O. Microencapsulated *n*-octacosane as phase change material for thermal energy storage. Solar Energy 2009;83:1757–63.
[40] Zhang H, Wang X. Synthesis and properties of microencapsulated *n*-octadecane with polyurea shells containing different soft segments for heat energy storage and thermal regulation. Solar Energy Materials & Solar Cells 2009;93:1366–76.
[41] 〈www.climator.com〉.
[42] 〈www.rubitherm.com〉.
[43] Cabeza LF, Castellon C, Nogues M, Medrano M. Use of microencapsulated PCM in concrete walls for energy savings. Energy and Buildings 2007;39:113–9.
[44] Ryu HW, Woo SW, Shin BC, Kim SD. Prevention of supercooling and stabilization of inorganic salt hydrates as latent heat storage materials. Solar Energy Materials and Solar Cells 1992;27:161–72.
[45] Fan YF, Zhang XX, Wang XC, Li J, Zhu QB. Super-cooling prevention of microencapsulated phase change material. Thermochimica Acta 2004; 413(1–2):1–6.
[46] Biswas DR. Thermal energy storage using sodium sulfate decahydrate and water. Technical note. Solar Energy 1977;19:99–100.
[47] Fang G, Li H, Yang F, Liu X, Wu S. Preparation and characterization of nano-encapsulated *n*-tetradecane as phase change material for thermal energy storage. Chemical Engineering Journal 2009;153:217–21.
[48] Fang Y, Kuang S, Gao X, Zhang Z. Preparation and characterization of novel nano-encapsulated phase change materials. Energy Conversion and Management 2008;49:3704–7.
[49] Khodadadi JM, Hosseinizadeh SF. Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage. International Communications in Heat and Mass Transfer 2007;34:534–43.
[50] Sukhorukov G, Fery A, Mohwald H. Intelligent micro- and nanocapsules. Progress in Polymer Science 2005;30:885–97.
[51] 〈www.teappcm.com〉.
[52] 〈www.pcmproducts.net〉.
[53] 〈www.microteklabs.com〉.
[54] 〈www.basf.com〉.
[55] 〈www.energain.dupont.com〉.
[56] 〈www.aegisbt.com〉.
[57] Rady M. Granular phase change materials for thermal energy storage: experiments and numerical simulations. Applied Thermal Engineering 2009;29:3149–59.
[58] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Heat transfer enhancement in a latent heat storage system. Solar Energy 1999;65(3): 171–80.
[59] Fan L, Khodadadi JM. Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renewable and Sustainable Energy Reviews 2011;15(1):24–46.
[60] Jegadheeswaran S, Pohekar SD. Performance enhancement in latent heat thermal storage system: a review. Renewable and Sustainable Energy Reviews 2009;13:2225–44.
[61] Ettouney HM, Alatiqi I, Al-Sahali M, Al-Ali SA. Heat transfer enhancement by metal screens and metal spheres in phase change energy storage systems. Renewable Energy 2004;29:841–60.
[62] Sari A. Form-stable paraffin/high density polyethylene composites as solid–liquid phase change material for thermal energy storage: preparation and thermal properties. Energy Conversion and Management 2004;45: 2033–42.
[63] Bellemare JV. Thermally reflective encapsulated phase change pigment. US Patent 2007;No. 0031652 A1.
[64] Regin AF, Solanki SC, Saini JS. Heat transfer characteristics of thermal energy storage system using PCM capsules: a review. Renewable and Sustainable Energy Reviews 2008;12:2438–58.
[65] Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. Energy Conversion and Management 2004;45:1597–615.
[66] Zhao CY, Zhang GH. Review on microencapsulated phase change materials (MEPCMs): fabrication, characterization and applications. Renewable and Sustainable Energy Reviews 2011;15:3813–32.
[67] Dutil Y, Rousse DR, Salah NB, Lassue S, Zalewski L. A review on phase-change materials: mathematical modeling and simulations. Renewable and Sustainable Energy Reviews 2011;15:112–30.
[68] Prakash J, Garg HP, Datta G. A solar water heater with a built-in latent heat storage. Energy Conversion and Management 1985;25(1):51–6.
[69] Bony J, Citherlet S. Numerical model and experimental validation of heat storage with phase change materials. Energy and Buildings 2007;39:1065–72.
[70] Talmatsky E, Kribus A. PCM storage for solar DHW: an unfulfilled promise? Solar Energy 2008;82:861–9.
[71] Ibanez M, Cabeza LF, Sole C, Roca J, Nogues M. Modelization of a water tank including a PCM module. Applied Thermal Engineering 2006;26:1328–33.
[72] Cabeza LF, Ibanez M, Sole C, Roca J, Nogues M. Experimentation with a water tank including a PCM module. Solar Energy Materials & Solar Cells 2006;90:1273–82.
[73] Mehling H, Cabeza LF, Hippeli S, Hiebler S. PCM-module to improve hot water heat stores with stratification. Renewable Energy 2003;28:699–711.
[74] Tyagi VV, Kaushik SC, Tyagi SK, Akiyama T. Development of phase change materials based microencapsulated technology for buildings: a review. Renewable and Sustainable Energy Reviews 2011;15:1373–91.
[75] Schossig P, Henning HM, Gschwander S, Haussmann T. Micro-encapsulated phase-change materials integrated into construction materials. Solar Energy Materials & Solar Cells 2005;89:297–306.
[76] Castellon C, Medrano M, Roca J, Nogues M, Castell A, Cabeza LF. Use of microencapsulated phase change materials in building applications. ASHRAE 2007.
[77] Douglas CH. Phase change materials in floor tiles for thermal energy storage. Topical report 2002; Colorado State University, USA.
[78] Castellon C, Medrano M, Roca J, Cabeza LF, Navarro ME, Fernandez AI, Lazaro A, Zalba B. Effect of microencapsulated phase change material in sandwich panels. Renewable Energy 2010;35:2370–4.
[79] Li J, Xue P, Ding W, Han J, Sun G. Micro-encapsulated paraffin/high-density polyethylene/wood flour composite as form-stable phase change material for thermal energy storage. Solar Energy Materials & Solar Cells 2009;93:1761–7.

[80] Kenisarin MM, Kenisarina KM. Form-stable phase change materials for thermal energy storage. Renewable and Sustainable Energy Reviews 2012;16:1999–2040.
[81] Nallusamy N, Sampath S, Velraj R. Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources. Renewable Energy 2007;32:1206–27.
[82] Esen M, Durmus A, Durmus A. Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. Solar Energy 1998;62(1):19–28.
[83] Kousksou T, Bruel P. Encapsulated phase change material under cyclic pulsed heat load. International Journal of Refrigeration 2010;33(8):1648–56.
[84] Song Q, Li Y, Xing J, Hu JY, Marcus Y. Thermal stability of composite phase change material microcapsules incorporated with silver nano-particles. Polymer 2007;48:3317–23.
[85] Davis DA, Hart RL, Work DE, Virgallito DR. Macrocapsules containing microencapsulated phase change materials. US Patent 2004;No. 6835334.
[86] Ma S, Song G, Li W, Fan P, Tang G. UV irradiation-initiated MMA polymerization to prepare microcapsules containing phase change paraffin. Solar Energy Materials & Solar Cells 2010;94:1643–7.
[87] Zhang XX, Tao XM, Yick KL, Wang XC. Structure and thermal stability of microencapsulated phase-change materials. Colloid and Polymer Science 2004;282:330–6.
[88] Salaun F, Devaux E, Bourbigot S, Rumeau P. Material containing microcapsules, in particular phase-changing material. US Patent 2009;No. 0291309 A1.
[89] Su J, Ren L, Wang L. Preparation and mechanical properties of thermal energy storage microcapsules. Colloid and Polymer Science 2005;284:224–8.
[90] Ohtsubo T, Tsuda S, Tsuji K. A study of the physical strength of fenitrothion microcapsules. Polymer 1991;32(13):2395–9.
[91] Roy SK, Sengupta S. An evaluation of phase change microcapsules for use in enhanced heat transfer fluids. International Communications in Heat Transfer 1991;18:495–507.
[92] Wei J, Kawaguchi Y, Hirano S, Takeuchi H. Study on a PCM heat storage system for rapid heat supply. Applied Thermal Engineering 2005;25:2903–20.
[93] Ettouney H, Alatiqi I, Al-Sahali M, Al-Hajirie K. Heat transfer enhancement in energy storage in spherical capsules filled with paraffin wax and metal beads. Energy Conversion and Management 2006;47:211–28.
[94] Castellon C, Nogues M, Roca J, Cabeza LF. Design of a plastic encapsulation for phase change materials (PCM) in buildings. Advanced thermal energy storage through phase change materials and chemical reactions feasibility studies and demonstration projects. Eighth workshop, 18–20 April 2005 , Kizkalesi, Turkey.
[95] Werner R. Compatibility of organic latent heat storage materials and plastic container materials. Heat Recovery Systems and CHP 1987;7(4):383–8.
[96] Sun G, Zhang Z. Mechanical strength of microcapsules made of different wall materials. International Journal of Pharmaceutics 2002;242:307–11.
[97] Hatfield JC. Encapsulation of phase change materials. US Patent 1987;No.4,708,812.
[98] Zhang X, Chao N, Zhang X, Xu J. Natural microtubule encapsulated phase-change materials and preparation thereof. US Patent 2010; No. 0071882A1.
[99] Darkwa J, Su O. Thermal simulation of composite high conductivity laminated microencapsulated phase change material (MEPCM) board. Applied Energy 2012;95:246–52.
[100] Majumdar P, Saidbakhsh A. A heat transfer model for phase change thermal energy storage. Heat Recovery Systems and CHP 1990;10(5/6):457–68.
[101] Teng YM, Akin JE. An effective capacity approach to Stefan problems using simple isoparametric elements. International Communications in Heat and Mass Transfer 1994;21(2):179–88.
[102] Qarnia HE. Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water. Energy Conversion and Management 2009;50:247–54.
[103] Costa M, Buddhi D, Oliva A. Numerical simulation of a latent heat thermal energy storage system with enhanced heat conduction. Energy Conversion and Management 1998;39(3/4):319–30.
[104] Dwarka K, Kim JS. Thermal analysis of composite phase change drywall systems. Trans ASME Journal of Solar Energy Engineering 2005;127:352–6.
[105] Long JY. Numerical and experimental investigation for heat transfer in triplex concentric tube with phase change material for thermal energy storage. Solar Energy 2008;82:977–85.
[106] Veerappan M, Kalaiselvam S, Iniyan S, Goic R. Phase change characteristic study of spherical PCMs in solar energy storage. Solar Energy 2009;83:1245–52.
[107] Wu S, Fang G, Liu X. Thermal performance simulations of a packed bed cool thermal energy storage system using *n*-tetradecane as phase change material. International Journal of Thermal Sciences 2010;49:1752–62.
[108] Arkar C, Medved S. Influence of accuracy of thermal property data of a phase change material on the result of a numerical model of a packed bed latent heat storage with spheres. Thermochimica Acta 2005;438:192–201.
[109] Zukowski M. Mathematical modeling and numerical simulation of a short term thermal energy storage system using phase change material for heating applications. Energy Conversion and Management 2007;48:155–65.
[110] Zivkovic B, Fujii I. An analysis of isothermal phase change of phase change material within rectangular and cylindrical containers. Solar Energy 2001;70(1):51–61.
[111] Kalaiselvam S, Veerappan M, Aaron AA, Iniyan S. Experimental and analytical investigation of solidification and melting characteristics of PCMs inside cylindrical encapsulation. International Journal of Thermal Sciences 2008;47:858–74.
[112] Stritih U. An experimental study of enhanced heat transfer in rectangular PCM thermal storage. International Journal of Heat and Mass Transfer 2004;47:2841–7.
[113] Tan FL, Hosseinizadeh SF, Khodadadi JM, Fan L. Experimental and computational study of constrained melting of phase change materials (PCM) inside a spherical capsule. International Journal of Heat and Mass Transfer 2009;52:3464–72.
[114] Ettouney H, El-Dessouky H, Al-Kandari E. Heat transfer characteristics during melting and solidification of phase change energy storage process. Industrial and Engineering Chemistry Research 2004;43:5350–7.
[115] Cho K, Choi SH. Thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. International Journal of Heat and Mass Transfer 2000;43:3183–96.
[116] Zukowski M. Experimental study of short term thermal energy storage unit based on enclosed phase change material in polyethylene film bag. Energy Conversion and Management 2007;48:166–73.
[117] Ismail KAR, Henrıquez JR. Solidification of PCM inside a spherical capsule. Energy Conversion & Management 2000;41:173–87.
[118] Ismail KAR, Henrıquez JR. Numerical and experimental study of spherical capsules packed bed latent heat storage system. Applied Thermal Engineering 2002;22:1705–16.
[119] Ismail KAR. Moraes RIR. A numerical and experimental investigation of different containers and PCM options for cold storage modular units for domestic applications. International Journal of Heat and Mass Transfer 2009;52:4195–202.
[120] Akgun M, Aydın O, Kaygusuz K. Experimental study on melting/solidification characteristics of a paraffin as PCM. Energy Conversion and Management 2007;48:669–78.
[121] Regin AF, Solanki SC, Saini JS. An analysis of a packed bed latent heat thermal energy storage system using PCM capsules: numerical investigation. Renewable Energy 2009;34:1765–73.
[122] Wu S, Fang G. Dynamic performances of solar heat storage system with packed bed using myristic acid as phase change material. Energy and Buildings 2011;43(5):1091–6.
[123] Royon L, Guiffant G. Investigation on heat transfer properties of slurry of stabilized paraffin during a melting process. Energy Conversion and Management 2011;52(2):1073–6.
[124] Gschwander S, Schossig P, Henning HM. Micro-encapsulated paraffin in phase-change slurries. Solar Energy Materials & Solar Cells 2005;89:307–15.
[125] Royon L, Guiffant G, Perrot P. Forced convection heat transfer in a slurry of phase change material in an agitated tank. International Communications in Heat and Mass Transfer 2000;27(8):1057–65.
[126] Zhang S, Niu J. Experimental investigation of effects of supercooling on microencapsulated phase-change material (MPCM) slurry thermal storage capacities. Solar Energy Materials & Solar Cells 2010;94:1038–48.
[127] Diaconu BM, Varga S, Oliveira AC. Experimental study of natural convection heat transfer in a microencapsulated phase change material slurry. Energy 2010;35:2688–93.
[128] Choi E, Cho YI, Lorsch HG. Forced convection heat transfer with phase-change-material slurries: turbulent flow in a circular tube. International Journal of Heat and Mass Transfer 1994;37(2):207–15.
[129] Zeng R, Wang X, Chen B, Zhang Y, Niu J, Wang X, Di H. Heat transfer characteristics of microencapsulated phase change material slurry in laminar flow under constant heat flux. Applied Energy 2009;86:2661–70.
[130] Charunyakorn P, Sengupta S, Roy SK. Forced convective heat transfer in microencapsulated phase change material slurries: flow in circular ducts. International Journal of Heat and Mass Transfer 1991;34(3):819–33.
[131] Cabeza L, Heinz A, Streicher W. Inventory of phase change materials (PCM). Technical report 2007; Graz University of Technology Austria.
[132] Chen Z, Fang G. Preparation and heat transfer characteristics of microencapsulated phase change material slurry: a review. Renewable and Sustainable Energy Reviews 2011;15:4624–32.
[133] Zhang P, Ma ZW, Wang RZ. An overview of phase change material slurries: MPCS and CHS. Renewable and Sustainable Energy Reviews 2010;14:598–614.
[134] Eames PC, Griffiths PW. Thermal behavior of integrated solar collector/storage unit with 65 °C phase change material. Energy Conversion and Management 2006;47:3611–8.
[135] Alvarado JL, Marsh C, Sohn C, Phetteplace G, Newell T. Thermal performance of microencapsulated phase change material slurry in turbulent flow under constant heat flux. International Journal of Heat and Mass Transfer 2007;50:1938–52.
[136] Yang R, Xu H, Zhang Y. Preparation, physical property and thermal physical property of phase change microcapsule slurry and phase change emulsion. Solar Energy Materials & Solar Cells 2003;80:405–16.
[137] Wang X, Niu J, Li Y, Wang X, Chen B, Zeng R, Song Q, Zhang Y. Flow and heat transfer behaviors of phase change material slurries in a horizontal circular tube. International Journal of Heat and Mass Transfer 2007;50:2480–91.
[138] Chen B, Wang X, Zeng R, Zhang Y, Wang X, Niu X, Li Y, Di H. An experimental study of convective heat transfer with microencapsulated phase change material suspension: laminar flow in a circular tube under constant heat flux. Experimental Thermal and Fluid Science 2008;32:1638–46.
[139] Zhang Y, Rao Z, Wang S, Zhang Z, Li X. Experimental evaluation on natural convection heat transfer of microencapsulated phase change materials

slurry in a rectangular heat storage tank. Energy Conversion and Management 2012;59:33–9.
[140] Hu X, Zhang Y. Novel insight and numerical analysis of convective heat transfer enhancement with microencapsulated phase change material slurries: laminar flow in a circular tube with constant heat flux. International Journal of Heat and Mass Transfer 2002;45:3163–72.
[141] Sabbah R, Farid MM, Al-Hallaj S. Micro-channel heat sink with slurry of water with micro-encapsulated phase change material: 3D-numerical study. Applied Thermal Engineering 2008;29:445–54.
[142] Zhang Y, Wang S, Rao Z, Xie J. Experiment on heat storage characteristic of microencapsulated phase change material slurry. Solar Energy Materials and Solar Cells 2011;95:2726–33.